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ORIGINAL ARTICLE

The relationships between bone variables and physical fitness across the BMI spectrum in young adult women

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Abstract

In this cross-sectional study we aimed to evaluate the relationship between physical fitness and bone variables across the body mass index (BMI) spectrum in women aged 20–35 years. The study included 13 underweight women (BMI < 18.5 kg/m^2), 24 normal weight women (BMI 18.5–24.9 kg/m^2), and 20 overweight/obese women (BMI ≥ 25 kg/m^2) aged between 20 and 35 years. Bone mineral density (BMD) and content (BMC) at the whole body, lumbar spine, and femoral neck, lumbar spine trabecular bone score, femoral neck geometry were assessed using dual-energy X-ray absorptiometry. Cardiorespiratory fitness and lower limb muscle power were estimated using the 20-m shuttle run test and the Sargent jump test, respectively. The associations between bone variables and physical fitness were different according to BMI categories. Correlations between physical fitness and bone parameters are particularly significant in normal BMI and less significant in low and high BMI. Multivariate ANCOVA regression models demonstrated that absolute VO_{2max} (L/min) is a strong determinant of all the bone parameters regardless of BMI. Implementing strategies for increasing VO_{2max} (L/min) by increasing lean mass and promoting resistance and/or high-intensity interval training could be effective to optimize bone health in underweight and overweight young adult women.

Keywords Bone · Cardiorespiratory fitness · Muscle power · Body mass index · Women

Introduction

The beginning of the adult years is considered an important opportunity to optimize bone health. At this age, environmental factors play a crucial role in helping the skeleton to reach its genotypic potential, to optimize its peak bone mass, and to enhance its geometry [1]. Identifying such environmental factors is crucial in order to develop effective intervention strategies to maximize the peak bone mass and reduce the risk of fractures later in life.

Body weight is a well-known environmental determinant of the overall bone health, particularly at the age of peak bone mass [2]. Alterations in bone metabolism and phenotype have been described in underweight as well as overweight or obese individuals. Low body weight is associated with lower bone mass [3–6], alteration in trabecular and cortical bone architecture, and increased risk of bone fracture [7–11]. On the other end of the body mass index (BMI) spectrum, overweight individuals have higher bone mass [12] but altered bone microarchitecture and increased fracture risk at specific bone sites [8, 13]. Body weight and

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composition changes, endocrine abnormalities [14–16] and physical fitness [17] variations are potential mechanisms that may explain the altered bone phenotype observed at the two extreme ends of BMI. Although the implication of body weight, lean mass (LM), fat mass (FM) and hormonal profile have been extensively described in the literature, the implication of physical fitness has not been thoroughly evaluated.

Physical fitness, which comprises muscle strength and cardiorespiratory fitness, has been correlated with bone mass in normal weight women. Several studies demonstrated that high cardiorespiratory fitness and muscle strength are associated with higher bone mass at the lumbar spine, proximal femur, distal tibia and fibula, and total hip [1, 18–20]. Limited data have assessed the associations between physical fitness and other bone health parameters such as bone architecture, particularly in overweight and underweight women. For this reason, we sought to identify in the present study, the relationships between physical fitness variables and bone mass, geometry, and texture [as evaluated by the trabecular bone score (TBS)] in a group of normal weight, underweight and overweight/obese young adult women. We hypothesized that there is a significant correlation between physical fitness including muscle power and cardiorespiratory fitness and bone density, geometry and TBS in normal weight women and that these correlations persist in underweight and overweight/obese women.

Materials and methods

Participants

This cross-sectional study included 13 underweight, 24 normal weight women, and 20 overweight/obese women healthy women aged between 20 and 35 years. This age was chosen to be closely representative of peak bone mass [21]. Participants are primarily healthy individuals who were recruited from three private universities in Beirut, Lebanon. Women suffering from diseases affecting bone metabolism, smokers, pregnant, amenorrheic, and those taking medications that may affect bone and calcium metabolism (corticosteroid or anticonvulsant therapy) were excluded from the study. All participants completed an interview about medical history including menstrual history and medication use. The work described has been carried out in accordance with the declaration of Helsinki. This study was approved by the Bellevue Medical Center Ethics Committee and written informed consent was obtained from all individual participants included in the study.

Anthropometrics and bone parameters

Body weight (± 0.1 kg) was taken with a battery-powered electronic scale and height (± 1 cm) was taken using a standard stadiometer. BMI was calculated as body weight divided by height squared (kg/m^2). BMI is the anthropometric variable that is widely used to screen for weight categories. The sample was divided into underweight (BMI < 18.5 kg/m^2), normal weight (18.5 ≤ BMI < 25.0 kg/m^2), and overweight/obese (BMI ≥ 25 kg/m^2) according to the World Health Organization criteria [22]. Body composition was measured by the dual-energy X-ray absorptiometry (DXA, GE Healthcare, Lunar iDXA System, version 13.60) including LM (kg) and FM (%). The coefficients of variation for FM and LM were 1.13 and 0.54%, respectively [23].

Bone mineral density (BMD, g/cm^2) and bone mineral content (BMC, g) at the level of the entire body, the lumbar spine (L1–L4), and the FN were evaluated using DXA. The coefficients of variation were less than 1% for BMC and BMD [18]. The trabecular bone score (TBS) at the lumbar spine, a surrogate of bone texture, was calculated following the analysis of the two-dimensional images of the DXA via the software "TBS iNsight calibration, version 2.1.0.0". TBS is considered normal if TBS is ≥ 1.350, partially degraded if TBS varies between 1.200 and 1.350, and degraded if TBS is ≤ 1.200 [24]. The structural geometry of cross-sections traversing the proximal femur at the FN was evaluated using the Hip Structural Analysis (HSA) program. GE Lunar software allowed us an automated calculation of the cross-sectional area (CSA, mm^2), the cross-sectional moment of inertia (CSMI, mm^4), and the sectional modulus (Z, mm^3) [25]. The coefficient of variation for CSA and Z of the FN evaluated by duplicate measurements in 10 participants was less than 3%.

Physical performance

Cardiorespiratory fitness was estimated using 20-m shuttle run test [26]. VO_{2max} was expressed either as an absolute rate (L/min) or as relative rate (mL/min/kg). VO_{2max} was also normalized to LM and expressed in mL/min/kg LM. The lower limb explosive strength was estimated using the Sargent jump test [27] and the best score from three attempts was recorded. The average muscle power (Watts) was calculated using Lewis formula [28].

Physical activity level

The physical activity pattern was assessed using the IPAQ (International Physical Activity Questionnaire) short version. With the three questions on vigorous, moderate, and walking activities, the questionnaire distinguishes the activity levels in three categories: low, moderate, and high. The interpretation of the IPAQ questionnaire was made according to the recommendations [29].

Dietary habits

Daily calcium and protein intake was evaluated using a validated semi-quantitative food frequency questionnaire [30, 31]. The intake of calcium and protein was compared to the dietary recommended intakes. The recommended dietary allowances (RDA) of calcium and protein were estimated at 1000 mg/day [32] and 0.8 g/kg/day, respectively [33].

Statistical analysis

All continuous variables were expressed as means ± standard deviations (SD). Continuous variables quantifying anthropometric parameters, dietary habits, physical fitness, and bone parameters were evaluated for normality using the Shapiro–Wilk test and for equality of variance using Levene's mean test. Non-normally distributed parameters were compared between subjects with low, normal and high BMI using the Kruskal–Wallis test with pairwise comparisons and Bonferroni adjustment. Normally distributed parameters were compared by one-way ANOVA or Welch's one-way ANOVA with pairwise comparisons by Hochberg's GT2 test or Games-Howell test. Univariate correlations between bone parameters and both anthropometric and physical fitness parameters were computed using Spearman's correlation test. In accordance to Cohen, a correlation coefficient of less than 0.30 represents a weak correlation; a correlation coefficient between 0.30 and 0.49 represents a moderate correlation; and a correlation coefficient of 0.50 or larger represents a strong correlation [34]. Multivariate ANCOVA regression models were computed with bone parameters as dependent variables, BMI class as an independent categorical variable, and FM (in %), VO_{2max} (in L/min) and muscle power (in W) as independent continuous variables. Pairwise comparisons were computed on the estimated marginal means of the ANCOVA model with Sidak adjustment. SPSS Statistics version 25.0 (IBM Corporation, New York, USA) was used for statistical analysis. All tests were two-tailed and the threshold for statistical significance was set at $\alpha < 0.05$. A trend for a difference was defined as p value greater than 0.05 and less than 0.15.

Results

Clinical characteristics

Mean values of age, anthropometric parameters, dietary calcium and protein intake, physical fitness subcomponents, and bone parameters are displayed in Table 1. Underweight women had significantly lower body weight, BMI, LM, and FM compared to normal weight and overweight/obese women ($p < 0.001$). Mean intake of calcium was less than the RDA in the three groups, ranging from 49 to 63% of the RDA. Protein intake was similar in the three groups and close to the RDA. The majority of the participants had low physical activity levels. Walking was the most popular physical activity practiced by the participants. Absolute VO_{2max} and VO_{2max} relative to LM were significantly reduced in underweight women when compared to normal weight women ($p < 0.005$). Women with high BMI levels presented higher absolute VO_{2max} and muscle power and lower VO_{2max} relative to body weight in comparison to women with normal BMI ($p < 0.05$). When compared to normal weight women, underweight women had significantly lower BMD at all sites, FN BMC, FN CSA, and FN CSMI ($p < 0.05$) and a trend toward lower WB BMC ($p = 0.079$), LS BMC ($p = 0.051$), FN Z ($p = 0.052$), and TBS ($p = 0.075$). TBS in underweight women was on the lower limit of its normal value and showed partially degraded microarchitecture in 38.5% of underweight women (vs. 16.7% in normal weight women and 20% in overweight women). Overweight women had significantly higher WB BMC and BMD, FN BMC and BMD, FN CSA and FN Z compared to normal weight women ($p < 0.05$).

Dietary intake, anthropometrics, and bone parameters

None of the bone parameters was significantly correlated with calcium and protein intake ($p > 0.05$ in all groups). The association between different bone parameters and anthropometric measures is presented in Table 2. In the overall population, body weight, BMI, LM, and FM were positively correlated with BMC and BMD at all sites, FN CSA, FN CSMI, FN Z and TBS ($p < 0.01$). Correlations between bone variables and anthropometrics are not the same across the BMI spectrum. In underweight and overweight women, LM was more closely related to bone mass and FN geometry than is FM. In underweight women, there was a strong correlation between LM, WB BMC and LS BMC ($p < 0.05$) and a trend toward a significant correlation between LM and FN CSA, and FN CSMI ($p < 0.15$). In overweight women, there was a strong correlation between LM and the overall bone parameters (except TBS) ($p < 0.01$).

Physical fitness and bone parameters

The relationships between VO_{2max}, lower limb muscle power and bone parameters are shown in Table 3. In the overall population, LM was strongly correlated with absolute VO_{2max} (L/min) ($r = 0.822$, $p < 0.001$) but not with

Table 1 Characteristics of the participants

	Low BMI ($n=13$)	Normal BMI ($n=24$)	High BMI ($n=20$)	p value
Age (years)	22.70 ± 2.67	23.28 ± 2.41	23.66 ± 4.26	NS
Anthropometric parameters				
Height (m)	1.63 ± 0.05	1.62 ± 0.06	1.59 ± 0.07	0.204
Weight (kg)	47.31 ± 2.43[a,b]	54.02 ± 5.04	77.48 ± 14.02[a,c]	< 0.001
BMI (kg/m^2)	17.72 ± 0.44[a,b]	20.52 ± 1.76	30.20 ± 4.43[a,c]	< 0.001
Lean mass (kg)	32.82 ± 2.49[a,b]	35.45 ± 3.18	40.93 ± 5.56[a,c]	< 0.001
Fat percentage (%)	27.81 ± 3.56[a,b]	31.31 ± 3.25	43.50 ± 4.58[a,c]	< 0.001
Dietary habits				
Calcium intake (mg/day)	507.63 ± 225.66	633.08 ± 225.44	498.21 ± 210.65	NS
% RDA of calcium	50.76 ± 22.57	63.31 ± 22.54	49.71 ± 21.06	NS
Protein intake (g/kg/day)	1.05 ± 0.27	0.96 ± 0.31	0.86 ± 0.14	NS
% RDA of protein	120.17 ± 49.29	120.32 ± 38.58	93.91 ± 41.22	NS
Physical fitness				
Muscle power (W)	524.61 ± 60.44[b]	568.39 ± 104.85	680.31 ± 100.25[a,c]	0.002
VO_{2max} (L/min)	1.43 ± 0.10[a,b]	1.69 ± 0.33	1.95 ± 0.32[a,c]	0.001
VO_{2max} (mL/min/kg)	30.13 ± 2.44[b]	31.33 ± 4.74	25.64 ± 2.42[a,c]	< 0.001
VO_{2max} (mL/min/kg LM)	43.54 ± 2.84[a,b]	47.66 ± 6.66	48.12 ± 5.24[c]	0.018
Level of activity (%)				
Low	7 (21.9%)	12 (37.5%)	13 (40.6%)	0.380
Moderate	3 (14.3%)	12 (57.1%)	6 (28.6%)	0.050
Bone measurements				
WB BMC (g)	1978.79 ± 124.94[b]	2109.78 ± 243.31	2342.83 ± 297.98[a,c]	< 0.001
LS BMC (g)	53.05 ± 7.05[b]	58.79 ± 8.79	64.25 ± 13.46[c]	0.010
FN BMC (g)	3.74 ± 0.60[a,b]	4.31 ± 0.75	4.98 ± 0.95[a,c]	< 0.001
WB BMD (g/cm^2)	0.98 ± 0.05[a,b]	1.05 ± 0.09	1.14 ± 0.11[a,c]	< 0.001
LS BMD (g/cm^2)	1.02 ± 0.08[a,b]	1.13 ± 0.13	1.21 ± 0.16[c]	< 0.001
FN BMD (g/cm^2)	0.82 ± 0.08[a,b]	0.92 ± 0.13	1.05 ± 0.17[a,c]	< 0.001
FN CSA (mm^2)	118 ± 14.73[a,b]	135.13 ± 20.46	157.95 ± 29.16[a,c]	< 0.001
FN CSMI (mm^4)	7640.46 ± 2291.85[a,b]	9143.13 ± 2484.83	10185.15 ± 3067.15[c]	0.029
FN Z (mm^3)	482.33 ± 106.45[b]	573.23 ± 131.63	614.74 ± 170.47[a,c]	0.035
LS TBS	1.36 ± 0.07[b]	1.40 ± 0.08	1.45 ± 0.12[c]	0.027

Low BMI, BMI < 18.5 kg/m^2; normal BMI, 18.5 ≤ BMI < 25 kg/m^2; high BMI, BMI ≥ 25 kg/m^2

RDA recommended dietary allowances, *BMI* body mass index, *WB* whole body, *LM* lean mass, *FN* femoral neck, *LS* lumbar spine, *BMC* bone mineral content, *BMD* bone mineral density, *WB* whole body, *CSA* cross-sectional area, *CSMI* cross-sectional moment of inertia, *Z* section modulus, *TBS* trabecular bone score

[a]Significantly different from normal BMI ($p<0.05$)

[b]Significantly different from high BMI ($p<0.05$)

[c]Significantly different from low BMI ($p<0.05$)

VO_{2max} relative to body weight (mL/min/kg) ($r=0.201$, $p=0.181$). Absolute VO_{2max} was strongly correlated with BMC and BMD at all sites, FN CSA, FN CSMI, and FN Z ($0.641<r<0.762$, $p<0.01$) and moderately correlated with TBS ($r=0.419$, $p<0.01$). When normalized to LM, VO_{2max} was moderately correlated with BMC and BMD at all sites, FN CSA, and TBS ($0.300<r<0.445$, $p<0.05$). When analyzing each subgroup separately, correlations between VO_{2max} normalized to body weight or LM and bone parameters were maintained only in normal weight individuals. In low BMI category, only absolute VO_{2max} was strongly correlated with WB BMC, FN BMC, FN BMD, FN CSA, FN Z, and TBS ($r>0.7$, $p<0.05$). When normalized to LM, VO_{2max} was strongly correlated with some bone parameters such as FN BMC, FN Z and TBS ($r>0.7$, $p<0.05$). In high BMI category, absolute VO_{2max} was highly correlated with WB BMC, FN BMC, FN BMD, and all FN geometry parameters ($0.619<r<0.872$, $p<0.05$).

Lower limb muscle power was significantly correlated with BMC and BMD at all sites and with all FN geometry parameters in the overall population (moderate-to-high correlation, $r>0.3$, $p<0.01$). When analyzing each subgroup

Table 2 Correlation coefficients between anthropometric measures and bone measurements

	Body weight (kg)	BMI (kg/m^2)	LM (kg)	FM (%)
Low BMI				
WB BMC (g)	0.640*	−0.391	0.731**	−0.324
LS BMC (g)	0.418	0.088	0.621*	−0.319
FN BMC (g)	0.080	−0.153	0.303	−0.195
WB BMD (g/cm^2)	0.230	−0.328	0.088	0.154
LS BMD (g/cm^2)	0.213	−0.471	0.407	−0.319
FN BMD (g/cm^2)	0.126	−0.264	0.082	0.181
FN CSA (mm^2)	0.162	−0.074	0.457†	−0.261
FN CSMI (mm^4)	0.140	0.129	0.495†	−0.176
FN Z (mm^3)	0.226	0.049	0.357	0.028
LS TBS	0.025	−0.179	−0.170	−0.159
Normal BMI				
WB BMC (g)	0.525**	0.043	0.691**	−0.230
LS BMC (g)	0.456*	−0.011	0.591**	0.066
FN BMC (g)	0.625**	0.397†	0.643**	0.226
WB BMD (g/cm^2)	0.397†	0.035	0.553**	−0.083
LS BMD (g/cm^2)	0.181	−0.086	0.309†	0.019
FN BMD (g/cm^2)	0.401†	0.300	0.464*	0.098
FN CSA (mm^2)	0.529**	0.349†	0.604**	0.088
FN CSMI (mm^4)	0.524**	0.372†	0.545*	0.066
FN Z (mm^3)	0.561*	0.435†	0.549*	0.157
LS TBS	−0.183	−0.077	−0.114	−0.234
High BMI				
WB BMC (g)	0.622**	0.183	0.681**	0.040
LS BMC (g)	0.491*	0.038	0.663**	−0.121
FN BMC (g)	0.740**	0.421†	0.701**	0.280
WB BMD (g/cm^2)	0.605**	0.280	0.649**	0.192
LS BMD (g/cm^2)	0.419†	−0.035	0.603**	−0.142
FN BMD (g/cm^2)	0.649**	0.373†	0.585**	0.277
FN CSA (mm^2)	0.708**	0.397†	0.678**	0.295
FN CSMI (mm^4)	0.712**	0.356†	0.701**	0.228
FN Z (mm^3)	0.726**	0.324	0.686**	0.130
LS TBS	0.321	0.233	0.253	0.239
Total				
WB BMC (g)	0.696**	0.535**	0.819**	0.397**
LS BMC (g)	0.543**	0.389**	0.704**	0.295*
FN BMC (g)	0.729**	0.630**	0.767**	0.522**
WB BMD (g/cm^2)	0.674**	0.583**	0.725**	0.508**
LS BMD (g/cm^2)	0.548**	0.445**	0.652**	0.379**
FN BMD (g/cm^2)	0.714**	0.643**	0.708**	0.545**
FN CSA (mm^2)	0.752**	0.653**	0.787**	0.553**
FN CSMI (mm^4)	0.574**	0.463**	0.669**	0.337*
FN Z (mm^3)	0.586**	0.466**	0.679**	0.334*
LS TBS	0.382**	0.379**	0.319*	0.303*

BMI body mass index, *LM* lean mass, *FM* fat mass, *WB* whole body, *LS* lumbar spine, *FN* femoral neck, *BMC* bone mineral content, *BMD* bone mineral density, *CSA* cross-sectional area, *CSMI* cross-sectional moment of inertia, *Z* section modulus, *TBS* trabecular bone score

*$p < 0.05$, **$p < 0.01$, †$0.05 < p < 0.15$

separately, muscle power was significantly correlated with BMC at all sites and FN geometry only in normal weight women. No consistent association between lower limb muscle power and bone measurements were found in underweight women. In high BMI, category muscle power was only correlated with WB BMC and FN Z (moderate-to-high correlation, $r > 0.4$, $p < 0.05$).

Multivariate analysis

All bone parameters (except for TBS) were no more significantly different between the three BMI categories after adjustment for FM (%), muscle power (W), and absolute VO_{2max} (L/min) (Table 4). These confounding factors explain between 41.7 and 65.2% of the variability of the bone variables. Multivariate analysis showed that absolute VO_{2max} is the most significant predictor of all bone variables among other confounded variables ($p < 0.05$).

Discussion

The current study aimed to evaluate the relationship between physical fitness and bone outcomes in overweight/obese and underweight women around the age of peak bone mass. The results reveal that VO_{2max} (L/min) is the strongest determinant of BMD/BMC, FN geometry parameters and TBS regardless of BMI.

In this study, underweight women appropriately presented the lowest values for BMC and BMD at all sites, FN CSA, and FN CSMI compared to women in the normal and high BMI categories. Furthermore, underweight women have lower L1–L4 TBS when compared to overweight and obese women. Using normative data of post-menopausal women, we demonstrated that the L1–L4 TBS is on the lower limit of normal (1.357 ± 0.071) in underweight women and that 38.5% of these women have partially degraded microarchitecture. Our findings are very similar to those reported in patients with anorexia nervosa [35]. Indeed, Donaldson et al. have shown that the mean value of TBS in anorectic patients is equal to 1.350 (± 0.10) and that nearly 40% of the patients have abnormal bone texture. Our findings add to the previous knowledge that low body weight is a serious problem for bone health [36–38] particularly if it occurs around the age of peak bone mass.

On the other end of the BMI spectrum, overweight women did show higher values of the majority of bone variables when compared to underweight and normal weight women. Our results support the body of available literature in view of the effect of high BMI on bone mass or architecture [12, 39]. However, women with high BMI presented similar TBS values when compared with women with normal BMI. This result is in accordance with our previous

Table 3 Correlation coefficients between VO_{2max}, muscle power, and bone measurements

	VO_{2max} (L/min)	VO_{2max} (mL/min/kg)	VO_{2max} (mL/min/kg LM)	Muscle power (W)
Low BMI				
WB BMC (g)	0.743*	0.244	0.524	0.240
LS BMC (g)	0.240	−0.049	0.048	0.263
FN BMC (g)	0.922**	0.683†	0.810*	0.228
WB BMD (g/cm²)	0.671†	0.390	0.667†	0.383
LS BMD (g/cm²)	0.443	0.342	0.429	0.419
FN BMD (g/cm²)	0.814*	0.537†	0.619†	0.216
FN CSA (mm²)	0.886**	0.537†	0.643†	−0.048
FN CSMI (mm⁴)	0.599†	0.244	0.357	−0.024
FN Z (mm³)	0.847*	0.259	0.821*	0.342
LS TBS	0.721*	0.561†	0.738*	0.132
Normal BMI				
WB BMC (g)	0.708**	0.588**	0.520**	0.662**
LS BMC (g)	0.652**	0.544**	0.523**	0.422*
FN BMC (g)	0.650**	0.449*	0.466*	0.548**
WB BMD (g/cm²)	0.686**	0.626**	0.567**	0.361
LS BMD (g/cm²)	0.513*	0.565**	0.516**	0.172
FN BMD (g/cm²)	0.585**	0.499*	0.489*	0.263
FN CSA (mm²)	0.706**	0.603**	0.570**	0.406*
FN CSMI (mm⁴)	0.504*	0.328	0.305†	0.451*
FN Z (mm³)	0.471*	0.256	0.266	0.468*
LS TBS	0.152	0.343	0.283	−0.051
High BMI				
WB BMC (g)	0.619*	−0.122	−0.095	0.685*
LS BMC (g)	0.416†	−0.024	−0.275	0.462†
FN BMC (g)	0.762**	−0.398	−0.029	0.559†
WB BMD (g/cm²)	0.504†	−0.083	−0.167	0.501†
LS BMD (g/cm²)	0.363	0.109	−0.222	0.315
FN BMD (g/cm²)	0.615*	−0.192	−0.011	0.378
FN CSA (mm²)	0.716**	−0.316	0.024	0.399
FN CSMI (mm⁴)	0.758**	−0.398	0.007	0.462†
FN Z (mm³)	0.872**	−0.247	0.082	0.667*
LS TBS	0.161	0.613*	0.411†	−0.070
Total				
WB BMC (g)	0.761**	0.039	0.410**	0.662**
LS BMC (g)	0.657**	0.062	0.300*	0.491**
FN BMC (g)	0.747**	−0.062	0.383**	0.637**
WB BMD (g/cm²)	0.713**	0.056	0.445**	0.463**
LS BMD (g/cm²)	0.620**	0.049	0.345*	0.397**
FN BMD (g/cm²)	0.715**	−0.042	0.391**	0.458**
FN CSA (mm²)	0.762**	−0.053	0.427**	0.514**
FN CSMI (mm⁴)	0.641**	−0.047	0.289†	0.434**
FN Z (mm³)	0.669**	0.032	0.269†	0.501**
LS TBS	0.419**	0.053	0.423**	0.238

LM lean mass, *WB* whole body, *LS* lumbar spine, *FN* femoral neck, *BMC* bone mineral content, *BMD* bone mineral density, *CSA* cross-sectional area, *CSMI* cross-sectional moment of inertia, *Z* section modulus, *TBS* trabecular bone score

*$p < 0.05$, **$p < 0.01$, †$0.05 < p < 0.15$

Table 4 Multivariate regression analysis

	B	SE	Partial Eta-squared	*p* value
WB BMC ($R^2 = 0.652$)				
Fat mass (%)	− 15.981	7.470	0.108	0.039
Muscle power (W)	0.686	0.367	0.084	0.069
VO_{2max} (L/min)	499.878	119.033	0.317	< 0.001
WB BMD ($R^2 = 0.512$)				
Fat mass (%)	− 0.001	0.003	0.003	0.734
Muscle power (W)	0.000	0.000	0.014	0.461
VO_{2max} (L/min)	0.208	0.050	0.312	< 0.001
L1–L4 BMC ($R^2 = 0.481$)				
Fat mass (%)	− 0.523	0.332	0.061	0.124
Muscle power (W)	0.006	0.016	0.003	0.723
VO_{2max} (L/min)	17.516	5.292	0.224	0.002
L1–L4 BMD ($R^2 = 0.423$)				
Fat mass (%)	− 0.005	0.005	0.028	0.301
Muscle power (W)	0.000	0.000	0.008	0.593
VO_{2max} (L/min)	0.239	0.079	0.194	0.004
FN BMC ($R^2 = 0.607$)				
Fat mass (%)	0.027	0.024	0.033	0.261
Muscle power (W)	0.001	0.001	0.038	0.225
VO_{2max} (L/min)	1.401	0.382	0.261	0.001
FN BMD ($R^2 = 0.537$)				
Fat mass (%)	0.003	0.005	0.009	0.556
Muscle power (W)	0.000	0.000	0.028	0.306
VO_{2max} (L/min)	0.317	0.073	0.332	< 0.001
FN CSA ($R^2 = 0.629$)				
Fat mass (%)	0.753	0.686	0.031	0.279
Muscle power (W)	− 0.032	0.034	0.024	0.342
VO_{2max} (L/min)	57.235	10.927	0.419	< 0.001
FN CSMI ($R^2 = 0.417$)				
Fat mass (%)	70.178	87.575	0.017	0.428
Muscle power (W)	− 0.408	4.302	0.000	0.925
VO_{2max} (L/min)	4890.013	1395.581	0.244	0.001
FN Z ($R^2 = 0.447$)				
Fat mass (%)	3.064	4.955	0.013	0.541
Muscle power (W)	0.215	0.314	0.015	0.499
VO_{2max} (L/min)	227.115	88.003	0.182	0.015
LS TBS ($R^2 = 0.420$)				
Fat mass (%)	− 0.005	0.003	0.071	0.097
Muscle power (W)	0.000	0.000	0.054	0.149
VO_{2max} (L/min)	0.109	0.051	0.108	0.038

WB whole body, *LS* lumbar spine, *FN* femoral neck, *BMC* bone mineral content, *BMD* bone mineral density, *WB* whole body, *CSA* cross-sectional area, *CSMI* cross-sectional moment of inertia, *Z* section modulus, *TBS* trabecular bone score

study demonstrating that being overweight is not associated with higher TBS in young adult women [40].

Body weight and composition and physical fitness are potential factors that may explain the bone phenotype seen in underweight and overweight women. In underweight women, low body weight was associated with low FM, LM, and VO_{2max} (L/min and mL/min/kg LM). When analyzing the correlation between all these environmental factors and bone phenotype, we demonstrated that only the absolute VO_{2max} (L/min) was significantly correlated with the majority of bone parameters. Furthermore, significant positive correlations were observed between VO_{2max} relative to LM (mL/min/kg LM) and some bone variables. These results indicate that the relationship between maximal aerobic power and bone may be partly related to LM [20]. Considering the strength of the association between VO_{2max} and bone parameters, the lack of relationship between lower limb muscle strength and bone in underweight women appears surprising. A low body weight might be associated with an inadequate muscular stimulus, and the strain may not be sufficiently heavy to induce positive effects on the skeleton [41].

Overweight women presented higher LM, FM, muscle power and absolute VO_{2max} (L/min) and lower VO_{2max} relative to body weight (mL/min/kg) in comparison to their lighter counterparts. To avoid penalizing heavier individuals by making values of VO_{2max} (mL/min/kg) seem lower, we normalized VO_{2max} to LM, and we demonstrated that VO_{2max} (mL/min/kg LM) did not differ significantly between normal weight and overweight women. When analyzing the correlation between anthropometric and bone measurements, we demonstrated that LM was more significantly correlated than FM with the majority of bone parameters. It is reasonable to consider that body weight does not confer mechanical advantage on bone unless accompanied by an increase in LM [15]. Among physical fitness subcomponents, only absolute VO_{2max} was significantly correlated with FN bone mass and geometry. This is in accordance with our previous studies established on overweight and obese men [17, 42].

Previous studies have demonstrated positive associations between bone mass and physical fitness variables in normal weight and overweight subjects [17–20]. Interestingly, we extended these findings to bone geometry and TBS in underweight subjects. Our findings confirm for the first time an independent relationship between absolute VO_{2max} (L/min) and bone outcomes (BMD and BMC at all sites, FN geometry, and TBS) whatever the status of BMI, particularly in low BMI category. Therefore, strategies for increasing LM and promoting physical activity such as resistance training and/or high-intensity interval training in order to increase VO_{2max} (L/min) could be effective to maximize bone mass and optimize bone architecture. Promoting physical activity from an early age, during the growth phase and around the age of peak bone mass, is very essential because it strongly influences bone mass and geometry parameters and may reduce the fracture risk later in life. However, a special attention should be considered when promoting physical activity in underweight women, particularly those with excessive dieting in order to prevent the risk of developing the female athlete triad syndrome [43].

Several limitations of our study should be considered. First, the cross-sectional nature of the present study did not permit us to investigate the link between physical fitness and bone health over an extended period. Second, the vitamin D status has not been taken into account in the present study. This vitamin plays a substantial role in bone metabolism and in maintaining physical performance [44]. Therefore, it should be evaluated when bone parameters and physical performance are examined. Third, it is largely accepted that muscle and bone are highly correlated at the mechanical level and evaluating muscle strength would be of great interest to better understand the correlation between muscle and bone at the two extremes of BMI. Fourth, the low number of subjects in each group may have prevented us from reaching statistical significance for some variables. Further studies with large sample size taking into account vitamin D status and muscle strength in underweight and overweight women are warranted in order to better understand the relationships between physical performance and bone outcomes across the BMI spectrum.

In conclusion, the associations of bone variables with VO_{2max} relative to body weight (mL/min/kg) and LM (mL/min/kg of LM) and muscle power are not the same across the BMI spectrum. Such correlations are particularly significant in normal BMI and less significant in low or high BMI. Absolute VO_{2max} (L/min) is correlated with the majority of bone outcomes as it is considered a strong determinant of bone phenotype regardless of BMI. We would therefore suggest that increasing VO_{2max} (L/min) by increasing LM and promoting physical activity is essential to optimize bone phenotype in young adult women.

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Compliance with ethical standards

Conflict of interest All authors have no conflicts of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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